Transport Barrier Analysis of LHD Plasmas in Comparison with Neoclassical Models

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Abstract

In the local Electron Cyclotron Heating (ECH) experiments, high electron temperature plasmas have been obtained in Compact Helical System (CHS), and recently in the Large Helical Device (LHD). The internal transport barrier (ITB) with strong positive radial electric field has been experimentally observed in CHS, which reduces neo-classical ripple transport and anomalous transport losses. The same physics picture is expected in LHD high temperature plasmas. Several ion temperature profiles are assumed for analyzing LHD experimental data, and it is found that the experimentally obtained electron thermal transport coefficients seem to roughly agree with neoclassical ripple transport outside the ITB region. However, around ITB region, about ten times higher than the neoclassical coefficients with strong ambipolar electric field prediction are obtained. The anomalous transport losses might be dominant and be reduced by this strong electric field shear around the ITB region.

Keywords:
internal transport barrier, radial electric field, neoclassical confinement, transport code simulation, helical system, LHD

1. Introduction

In the helical plasma confinement systems, the neoclassical ripple transport is supposed to be serious in the high temperature reactor regime. The strong electric field can be utilized for improving the plasma confinement in addition to the transport optimization by changing magnetic field configurations. High central electron temperature plasmas with positive electric potential have been obtained in the centrally focused Electron Cyclotron Heating (ECH) experiment of the Compact Helical System (CHS) [1]. The formation of this internal transport barrier (ITB) is correlated with the reduction of density fluctuation and the shear of electric field. In CHS it was found that the ITB is related to neoclassical positive electric field in the low-density regime [1]. Recently in the Large Helical Device (LHD) we have obtained a ten keV electron temperature plasma using centrally focused Gaussian beam at the fundamental and second harmonic resonances [2]. The threshold on the appearance of ITB in LHD is related to the plasma density and the heating power.

Here, LHD transport analyses using experimentally obtained radial profiles are described focusing on neoclassical transports with radial electric field effects. The ion temperature profile effects on electron confinement are also clarified.

2. Transport Barrier Formation in LHD

In the fifth campaign of the LHD experiment, the hot electron temperature operations have been performed using ~ 1 MW ECH heating power [2].

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3. Model of Transport Analysis

The steady-state transport equations solved here are as follows:

\[ \frac{3}{2} \frac{\partial}{\partial \rho} (n_e T_e) = - \frac{1}{V_e} \frac{\partial}{\partial \rho} (V_e Q_e) + P_{n_e}(\rho) = 0 \]

\[ \frac{3}{2} \frac{\partial}{\partial \rho} (n_e T_i) = - \frac{1}{V_i} \frac{\partial}{\partial \rho} (V_i Q_i) + P_{n_i}(\rho) = 0. \]  (1)

The heat flux is a summation of neoclassical symmetric term \( Q_{sym} \) (Hazeltine-Hinton (HH) formula for electron and Chang-Hinton (CH) formula for ion), neoclassical ripple term \( Q_{rip} \) and anomalous transport term \( Q_{anom} \):

\[ Q_i = Q_{sym,i} + Q_{rip,i} + Q_{anom,i} \quad (k = e, i) \]  (2)

Here, the effective ripple diffusivities, \( X_{rip,e} \) and \( X_{rip,i} \), are defined as

\[ Q_{rip,i} = - X_{rip,i} \left[ T_i \langle (\nabla \rho)^2 \rangle \frac{\partial n_i}{\partial \rho} - n_i E_i \right] \]

\[ = - X_{rip,i} n_e \langle (\nabla \rho)^2 \rangle \frac{\partial T_i}{\partial \rho} \quad (k = e, i) \]  (3)

with neoclassical ripple coefficients \( X_t \) and \( X_e \). The helical magnetic field harmonics and self-consistent radial electric field effects are included [5]. The total neo-classical transport coefficients are obtained by

\[ X_{n,e} = X_{11,e} + X_{rip,e} \]

\[ X_{n,i} = X_{11,i} + X_{rip,i} . \]  (4)

These values are compared with the following effective experimental transport coefficients \( X_{exp} \):

\[ X_{exp,e} = - \frac{Q_{n,e}}{n_e \langle (\nabla \rho)^2 \rangle \frac{\partial T_e}{\partial \rho}} \]

\[ X_{exp,i} = - \frac{Q_{n,i}}{n_i \langle (\nabla \rho)^2 \rangle \frac{\partial T_i}{\partial \rho}} . \]  (5)

The ECH power deposition is modeled by the following power localization to the central region with the width of \( \rho_{ref} = 0.1 \):

\[ P_{ECH}(\rho) = \frac{1}{\exp \left[ \left( \rho / \rho_{ref} \right)^4 \right]} . \]  (6)

which roughly agrees with the results of the ray-tracing analysis.

The high electron temperature can be expected in the case of centrally focused ECH experiment. Related to the ITB shot of Fig. 1, the following five cases have
been analyzed: (1) full simulation with empirical and neoclassical transport models without using experimental profile data, (2) experimental density profile is used, (3) experimental density \(n_e\) and electron temperature \(T_e\) profiles are used, (4) experimental density and temperature profiles are used and ion temperature \(T_i\) profile with experimental central value is assumed, and (5) drift wave model full simulation. We found that the electron temperature critically depend on ECH central power deposition profile and electron density profile. In this paper, the data analysis with experimental \(n_e\) and \(T_e\) data and the modeled \(T_i\) profile (case (4)) is focused as shown in the next chapter. Other simulation results will be reported somewhere in the future.

4. Experimental Data Analysis in Comparison with Neoclassical Theory

In order to get electron and ion transport coefficients, the parabolic \(T_i\) profile with experimental central value \(T_{i0}\) is assumed.

\[
T = T_{i0}(1 - \rho^2)^m
\]

Three cases were analyzed; (1) reference parabolic case \((l=1,m=2)\), (2) flat case \((l=2,m=2)\), and (3) peaked case \((l=1,m=4)\). We obtained experimental transport coefficients denoted as "Exp" as shown in Fig. 2 in the case of reference-\(T_i\) profile. The neoclassical value (NC) is a summation of axi-symmetric coefficient (NC(HH) for electron or NC(CH) for ion) and ripple transport coefficient (NC(ripple)). The transport coefficient with zero ambipolar potential is also plotted as "NC(E=0)". The experimental transport coefficient near ITB \((\rho_p \sim 0.2)\) obtained here seem to be one order of magnitude higher than the neoclassical value (HH plus ripple transport for electron, CH plus ripple transport for ion). The strong positive radial electric field ("electron root") in the center has been predicted by the analysis. The negative electric field region ("ion root") is obtained outside the central region \((\rho_p > 0.4)\). The radial profile shape of zero-potential transport coefficient does not fit the experimental value for both electron and ion. The reduc-

\[
\begin{align*}
\chi_e & = 0.06 \times (\rho_p)^{0.2} \\
\chi_i & = 0.04 \times (\rho_p)^{-0.2}
\end{align*}
\]

\[
\begin{align*}
E_r & = 300 - 200 \rho_p \\
\chi_e & = 0.01 \times (\rho_p)^{-1.2} \\
\chi_i & = 0.01 \times (\rho_p)^{0.2}
\end{align*}
\]
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More detailed analysis should be carried out by comparing with experimental radial electric potential and ion temperature profiles which will be obtained in the near future experiment.

5. Summary and Discussion

Several experimental data analyses have been carried out for high electron temperature discharges in LHD electron cyclotron heating experiments, and came to the following conclusions;

(1) The thermal diffusivities of the hot electron temperature discharges in LHD have been obtained and compared with the neoclassical values.

(2) The prediction of radial electric field production by the neoclassical theory strongly depends on the assumed ion temperature profile. However, the central region is not sensitive to the ion temperature profile.

(3) Experimentally obtained transport coefficients roughly agree with neoclassical values at normalized radius $\rho_p \sim 0.5$, however around $\rho_p \sim 0.2$ (ITB region) they are several or ten times
higher than the neoclassical value. The anomalous transport might be dominant around here and be reduced by the strong electric field shear.

More precise analyses should be continued for LHD in comparison with CHS, using additional future experimental data such as electric potential profile, ion temperature profile, density and power scan data, and so on. The anomalous transport model simulation with strong electric field shear will be given somewhere in the future.

References